SUCCESSION AND RELATION OF LAVAS IN THE GREAT BASIN REGION[1]

RICHTHOFEN'S STUDIES

THE Great Basin was early recognized as showing a variety of Tertiary lavas which are identical over large areas, and erupted in somewhat the same succession. The first deductive studies from these facts were made by the Baron von Richthofen,[2] and were published in 1867. Partly as a result of observations in the rocks of the Great Basin and of California, and partly from studies in the volcanic regions of Europe, Richthofen arrived at what he considered to be the natural law for the sequence of massive eruptions, applicable to all centers of volcanic activity. According to him the order of succession was :

1. Propylite.
2. Andesite.
3. Trachyte.
4. Rhyolite.
5. Basalt.

This law of succession was accepted without much question for a long time by many European and American geologists.

THEORIES OF THE ORIGIN OF IGNEOUS ROCK DIFFERENCES PREVIOUS TO RICHTHOFEN[3]

By way of summarizing briefly the difference between Richthofen's theories and those of his predecessors, it may be remarked that Bunsen, who was one of the first to speculate concerning rock differences, after visiting Iceland and studying the volcanic phenomena, formed the hypothesis of two distinct magmas or bodies of lavas, one acid, and the other basic; the normal "trachytic" and the normal "pyroxenic" magmas,

[1] Published by permission of the Director of the United States Geological Survey.

[2] "Natural System of Volcanic Rocks," Mem. California Acad. Sci., Vol. I, p. 36.

[3] See Monograph XX, U. S. Geol. Surv., p. 273.

as he called them. He regarded all lavas between these extreme types as mixtures of the two in varying proportions. It will be noted that Bunsen's explanation[1] was essentially a theory of mixing rather than of differentiation.

Durocher[2] accepted Bunsen's idea of the existence of an acid and a basic magma, and admitted the possibility of a mingling of the two in certain cases to produce intermediate types, but did not follow this idea to the extent of Bunsen. Durocher proposed the hypothesis, which was not substantiated by much study of volcanic action in the field, that certain lavas may be produced by segregation, or differentiation, *i. e.*, by the breaking up of a magma into several different parts, as a result of chemical activity. Durocher's ideas of the origin of igneous rocks, therefore, include the idea of segregation, or differentiation, together with that of mixing.

Roth[3] later also held that a magma may segregate during crystallization into lavas of different mineralogical composition, although his ideas of the processes of differentiation were not specifically identical with those of Durocher, who had considered these processes analogous with those by which metals are segregated in metallurgical operations.

Von Waltershausen,[4] after studying the lavas of Sicily and Iceland, came to the conclusion that lavas were derived from a zone of molten material between the earth's crust and its solid interior, and that the material arranged itself according to the laws of gravitation, so that the most siliceous lava, which is also the lightest, was nearest the surface; the most basic at the bottom, and the intermediate lavas in the zones between. His own observations in the field seemed to point out that the lavas were

[1] Ueber die Processe der vulkanischen Gesteinsbildung Islands, Poggendorf's Annalen, 1851, Band 83, pp. 197–272.

[2] Essai de Pétrologie comparée, Ann. d. Mines, Paris, 5th series, 1857, Tome XI, pp. 217–259.

[3] Tabellarische Uebersicht der Geistens-Analysen, mit kritischen Erläuterungen, Berlin, 1861.

[4] Ueber die vulkanischen Gesteine in Sicilien und Island und ihre submarine Umbildung, Göttingen, 1853.

thrown out according to their supposed superposition, the order being, therefore, regularly from acid to basic lavas.

KING'S WORK AND ITS LATER MODIFICATIONS

The first careful work on the lavas of the Great Basin was done during the 40th Parallel Survey, the field-work of which was done chiefly by Messrs. Hague and Emmons, while the petrographic work was by Professor Zirkel, and the general results and deductions were made by the director, Mr. Clarence King.[1] Mr. King accepted in general the law of succession of volcanic rocks, as laid down by Richthofen, but subdivided the lavas of each member of the succession, and united the fourth and fifth members — the rhyolite and basalt[2] — under a general term, "Neolite." The natural order, as interpreted by King, was as follows:

Order	Subdivision
1. Propylite	*a.* Hornblende propylite. *b.* Quartz propylite. *c.* Augite propylite.
2. Andesite	*a.* Hornblende andesite. *b.* Quartz andesite (Dacite). *c.* Augite trachyte.
3. Trachyte	*a.* Hornblende-plagioclase trachyte. *b.* Sanidine trachyte (quartziferous). *c.* Augite trachyte.
4. Neolite	*a.* Rhyolite. *b.* Basalt.

As regards the laws maintained by Richthofen and King for the Great Basin, it is necessary to observe first of all that the first member — propylite — was proved by Mr. George F. Becker[3] to be simply a decomposed phase of the andesite in the Washoe district, instead of a separate rock, as supposed by Richthofen

[1] Geological Explorations of the 40th Parallel, Vol. I, p. 545 et seq.

[2] This colligation of rhyolite and basalt was made by King on the basis of their close association in the field. His explanations of this fact, however, were essentially different from later ones, now generally accepted, and first advanced by Mr. Hague, Mon. XX, U. S. Geol. Surv.

[3] Geology of the Comstock Lode, Washoe District, Mon. III, U. S. Geol. Surv., p. 88.

This conclusion was corroborated by subsequent investigators in different parts of the world, so that the term has passed out of use. It has also been proved by Mr. Becker's studies, and later by those of Messrs. Hague and Iddings,[1] that the trachytes of Richthofen and of the 40th Parallel Survey, as determined by Zirkel, are mainly andesites — in part hornblende-mica andesite, and in part hypersthene-augite andesite (the latter rock corresponding more nearly to the augite-trachyte of Zirkel), while a smaller proportion are dacites, and some are probably rhyolites. It has been determined by these investigators that trachyte is conspicuously absent in the province of the Great Basin. The reason for Zirkel's false classification was the lack of means at that time to determine the feldspars, so that the plagioclases were determined as sanidine, since they showed little or no striation.

SUCCESSION OF LAVAS PREVIOUSLY DESCRIBED IN THE GREAT BASIN AND VICINITY

Eureka district.— In the course of a careful study of the volcanic rocks of the Eureka district in Nevada, Mr. Hague[2] arrived at the following succession of lavas at this center of volcanic activity:

1. Hornblende andesite.
2. Hornblende-mica andesite.
3. Dacite.
4. Rhyolite.
5. Pyroxene andesite.
6. Basalt.

Washoe district.— In the Comstock or Washoe district, at the southern end of the Virginia Range, Mr. Becker[3] found the following succession of igneous rocks:

1. Granite.
2. Diorite.
3. Quartz-porphyry.

[1] "Volcanic Rocks of the Great Basin," Amer. Jour. Sci., June 1884, p. 453. Geology of the Eureka District, Mont. XX, U. S. Geol. Surv., p. 230 et seq.

[2] Mon. XX, U. S. Geol. Surv., p. 290. [3] Mon. III, U. S. Geol. Surv., p. 380.

4. Earlier diabase.
5. Later diabase.
6. Earlier hornblende andesite.
7. Augite andesite.
8. Later hornblende andesite.
9. Basalt

Messrs. Hague and Iddings,[1] after a careful microscopic study of the collections made by Mr. Becker in the Comstock region, arrived at somewhat different conclusions, although agreeing with Mr. Becker as to the identity of propylite with andesite. They concluded that the granular diorite and diabase, and the augite andesite, were variations of the same body, the granular rocks representing textural differences brought on by slowly cooling in the deeper parts of the extruded mass, while the finer-grained porphyritic rocks represented the periphery of the same. To substantiate their conclusion they show the existence of all possible gradations between the extreme types They also conclude that the porphyritic diorite is identical with the hornblende andesite, and the mica diorite with the later hornblende andesite, the difference in each case being due to variations of texture. The quartz-porphyry of Mr. Becker they regard as partly dacite, and partly rhyolite; while the later diabase, or "black dike," they regard as identical with the effusive basalt. They find, also, that the pyroxene and hornblende andesites are difficult to separate, but that these are cut through by hornblende andesites, dacites, rhyolites, and basalts. The succession of lavas in this district is, according to Mr. Hague:

1. Pyroxene-hornblende andesite (inner portions pyroxene-hornblende diorite porphyry, and pyroxene-hornblende diorite).
   Period of volcanic rest and denudation.
2. Hornblende-mica andesite.
3. Dacite.
4. Rhyolite.
5. Pyroxene andesite.[2]
6. Basalt.

[1] "On the Development of Crystallization in the Igneous Rocks of Washoe," Bull. 17, U. S. Geol. Surv.

[2] See Mon. XX, U. S. Geol. Surv., p. 281. Compare the succession in the adjacent Pine Nut Range, p. 628.

The hornblende andesite of Eureka is correlated with the hornblende-mica andesite of Washoe, while the pyroxene-hornblende andesite of Washoe is supposed to belong to an earlier period, not represented at Eureka; otherwise the succession of lavas at the two centers of eruption is considered to be similar and the different extrusions in general contemporaneous.

Sierra Nevada.— Mr. H. W. Turner[1] published in 1895 a résumé of the age and succession of igneous rocks in the Sierra Nevada. According to him the succession of the Tertiary volcanics in this region is as follows:

1.	Acid - - - -	Rhyolite — massive and fragmental.
2.	Basic - - -	Older basalt — always (?) massive.
3.	Intermediate - -	Hornblende-pyroxene andesite—chiefly tuff and breccia.
4.	Intermediate to acid -	Fine-grained pyroxene andesites — massive
5.	Basic - - - -	Doleritic basalts — massive.
6.	Basic - - -	Other basalts — massive.

In 1898 Mr. F. L. Ransome[2] published a critical study of a portion of the western slope of the Sierra Nevada, in the Sonora and Big Trees region — a locality, it may be noted, much nearer to the Washoe district than the Washoe is to Eureka. Mr. Ransome succeeded in classifying more accurately than had hitherto been done some of the intermediate lavas, determining rocks that had previously been classified variously as basalts, trachytes and andesites as belonging to the monzonitic family, intermediate between the granitic and dioritic families. For the volcanic variety of monzonite he proposed the term "latite." The succession of the Tertiary lavas in the region studied by Mr. Ransome is as follows:

1. Biotite rhyolite.
   Rhyolite tuffs.
2. Olivine-basalt.
3. Hornblende-pyroxene andesite brecca.

[1] JOUR. GEOL., Vol. III, No. 4, May–June 1895.

[2] Bull. 89, U. S. Geol. Surv. Also Amer. Jour. Sci., May 1898, 4th series, Vol. V, p. 355.

4. Latite { Augite-biotite hornblende latite.
   Biotite-augite latite.
5. Hornblende-pyroxene andesite breccia.
6. Olivine-basalt.

Tintic district.— Passing from the Sierra Nevada and the western border of the Great Basin (from the Sonora region and the Washoe district) eastward past Eureka, we will next cite the record of Tertiary vulcanism in the Tintic Range, which lies south of Salt Lake and southwest of Utah Lake, and is approximately the same distance from Eureka as Eureka is from Washoe. This region has been studied by Messrs. Tower and Smith.[1] The succession of lavas is as follows:

1. Biotite rhyolite.
2. Pyroxene-hornblende-biotite andesite — tuffs and breccias.
3. Pyroxene-hornblende andesite (latite).
4. Olivine-basalt.

The rhyolitic flows of the first member of the succession given above are known to be continuous and contemporaneous with dikes of rhyolite which, on account of their somewhat different habit, were given the name of *quartz-porphyry* in the text. This intrusive rhyolite appears to be susceptible of correlation with the rhyolite or "quartz-porphyry," described by the writer,[2] from the northern end of the Oquirrh Range, which lies south of the Tintic district (Eagle Hill porphyry). The rhyolite in the Tintic district is known to be later than Upper Eocene.

The pyroxene-hornblende andesites (or latites) described by Messrs. Tower and Smith are regarded by them as belonging to the same general body as certain large masses of granular monzonite with which they are connected by transitional phases; the monzonite representing portions of the magma which have consolidated as intrusive masses under conditions favoring better crystallization than those under which the extrusive sheets of pyroxene andesite (or latite) have consolidated. These

[1] "Geology and Mining Industry of the Tintic District, Utah," Nineteenth Annual Rept. U. S. Geol. Surv., Part III, Economic Geol., p. 632.

[2] J. E. SPURR, "Economic Geology of the Mercur Mining District," Sixteenth Ann. Rept., Part II, p. 377.

transitions from typical fine-grained extrusives to porphyritic and to coarse granular intrusive rocks are highly interesting in themselves and by comparison with the similar phenomena which Messrs. Hague and Iddings[1] have found in the andesite and basalts of the Washoe district. The present writer has also found similar transitions, to be described elsewhere.

SUCCESSION OF LAVAS AT OTHER POINTS IN THE GREAT BASINS

During the past season's field work the writer has observed the succession of lavas at many different points in the Great Basin. From the nature of the work the time for study was in each case very restricted, so that the records given below are sometimes very likely incomplete.

Pine Nut Range.—The Pine Nut Range is interesting on account of lying immediately south of the Virginia Range and the Washoe district, and because the lavas of this district are easily recognizable in it. The range was crossed at two points, one east from Dayton and one east from Genoa. The succession of lavas appears to be as follows:

1. Rhyolite (intimately connected and probably contemporaneous with granite of similar constitution).
   Rhyolite sands and conglomerates (formed during long period of erosion).
2. Hornblende-pyroxene-biotite andesite (in portions sufficiently removed from the surface the typical glassy or microcrystalline groundmass of the lava becomes coarser, leading to the formation of diorite porphyry and monzonite porphyry).
3. Hornblende-mica andesite.
   Period of denudation.
4. Rhyolite (Shoshone Lake period ?).
5. Hornblende-pyroxene andesite, tuffs, and breccias (Shoshone Lake period).
6. Rhyolite.
7. Basalt (Pleistocene).

Of these extrusives the first appears to have been greatest in amount and the latter ones in general progressively less and less, in the order of their arrival.

[1] Bull. 17, U. S. Geol. Surv.

Sweetwater Range.—The Sweetwater Range may next be considered, since it lies south of the Pine Nut Range and shows very nearly the same rocks. It is separated from the Pine Nut Range only by the Walker River Valley, while at its southern end it connects with the Sierras, of which it may thus be considered a spur.

The observed succession of lavas in this range is as follows:

1. Rhyolite (closely connected and perhaps contemporaneous with granites of similar composition).
2. Hornblende-pyroxene andesite.
   Epoch of erosion and subsequent formation of Shoshone Lake.
3. Hornblende-pyroxene andesite, tuffs and breccias.
4. Hornblende-biotite latite.
5. Basalt.

Gabb's Valley Range.—In the lavas of Gabb's Valley and the Gabb's Valley Range, which lies just east of Walker Lake, the following succession was made out:

1. Biotite andesite.
2. Biotite rhyolite.
3. Hypersthene-hornblende aleutite.[1]
4. Augite basalt.

A granular rock, which had every appearance of being effusive, was also found in Gabb's Valley, and on examination proved to be a hornblende-biotite quartz-monzonite. This, however, is not included in the list, since its exact position is uncertain. It is very likely earlier than all the others and is perhaps contemporaneous with the biotite-hornblende quartz-monzonite, which forms the oldest rock in the Walker River Range, being more ancient than the granite.

Silver Peak Mountains.—Mr. H. W. Turner, who has studied the volcanic record in the Silver Peak district, has kindly supplied the writer with the preliminary statement that in general the succession of lavas here is as follows:

1. Rhyolite.
2. Andesite.
3. Basalt.

[1] See American Geologist, April 1900, p. 230.

Ralston Desert.— According to observations made by the writer, the succession of lavas in the Ralston Desert is as follows:

1. Rhyolite and tordrillite[1] (earlier).
2. Rhyolites, often glassy (late Pliocene).
3. Olivine-basalt (Pleistocene).

Practically the same succession is seen in the Kawich Range and in the Reveille Range.

Lake Mono Basin.[2]— In the basin of Lake Mono, according to Professor Russell, we have extensive Pleistocene volcanic activity, the lavas being basalt, hypersthene andesite verging on basalt, and rhyolite. Older than these is a hornblende andesite. The succession in this basin is, then:

1. Hornblende andesite.
2. Basalt, hypersthene andesite verging on basalt, rhyolite.

The relative age of the lavas under 2 was not determined, but they are all regarded as Pleistocene.

Toyabe Range.— In the southern end of the Toyabe Range the known succession of Tertiary lavas is as follows:

1. Biotite rhyolite (closely associated and perhaps contemporaneous with intrusive biotite granite).
2. Augite basalt (Pleistocene).

Schell Creek Range.— In the Schell Creek Range, near Schellbourne, we have the following succession of lavas:

1. Biotite rhyolite (flows often glassy).
2. Pyroxene aleutite (probably late Pliocene).

Egan Range.— In the Egan Range the following lavas were found:

1. Dacite-andesite.
2. Basalt.

Meadow Valley Canyon.— In the Meadow Valley Canyon (southward from Pioche) we have one of the best exposures of Tertiary lavas and their associated sediments which has yet been

[1] See Classification of Igneous Rocks according to Composition, J. E. SPURR, Am. Geol., April 1900, p. 230.

[2] Quaternary History of Mono Valley, California; Eighth Ann. Rept. U. S. Geol. Surv., Part I, p. 374, 379, etc.

found in Nevada. The completeness of the section enables one to see how complicated the history of Tertiary vulcanism and sedimentation is, but the following is the general succession :

1. Biotite rhyolite.
   Rhyolite tuffs and sands.
2. Pyroxene andesite, tuffs and breccias.
   Biotite-hornblende quartz-latite (basic).
   Biotite-hornblende dacite.
   Biotite-hornblende rhyolite, and tordrillite (heavy flows).
   Thin-bedded rhyolite (Pliocene).
3. Pyroxene olivine-basalt.
   Rhyolite-tordrillite. (Pleistocene.)

Funeral Range.—The volcanic activity of the Funeral Range has not been very well observed, but the following is part at least of the succession :

1. Biotite andesite (Eocene or Miocene).
2. Olivine-basalt.

Panamint Range.— In the Panamint Range the following succession of lavas has been observed:

1. Feldspathic lavas of medium acidity; species undetermined.
   Rhyolite.
2. Andesite (late Eocene or Miocene).
3. Pyroxene aleutites and basalts, often olivine-bearing (late Pliocene or Pleistocene).

Randsburg region.—In the mountains in the vicinity of the mining camp of Randsburg, in southern California, the writer observed the following succession:

1. Biotite rhyolite (early Eocene ?).
   Rhyolitic tuffs and sands.
2. Hornblende-pyroxene-biotite aleutite.
3. Pyroxene basalt
   Pyroxene olivine-diabase porphyry (dike). (Pleistocene.)

Coso Range.—According to Mr. Fairbanks,[1] the following is the succession of lavas in this range, roughly stated:

1. Rhyolites and andesites.
2. Basalts.

[1] Am. Geol., Vol. XVI, February 1896, p. 73.

Daggett or Calico region.—Southward, in the middle of the Mojave Desert, at Daggett, or Calico (which is on the Mojave River and also on the Santa Fé Railway), great masses of rhyolite have been described,[1] underlying the borax-bearing lake beds which are probably, in part at least, Upper Eocene. These rhyolites are plainly the same as those in the Coso Range and in the Randsburg region.

SUCCESSION OF LAVAS IN THE GREAT BASIN REGION IN GENERAL

In the field it is evident that the same lavas occur in many different localities throughout the Great Basin region, in much the same relative quantity, having nearly the same mineralogical composition, and giving evidence of about the same relative age. Moreover, where two or more of these lavas are found close together, their order of succession is found to be in general nearly the same, although at any given place certain members of the series may be lacking. In no single locality has the complete succession, as indicated by the correlation of all the different sections, been observed; but in order to find it we may fill gaps in one place from the observations in another. In correlating similar lavas erupted at different points, we must consider not only the succession but the relative age of each, so far as this is known. The evidence of this age will be briefly outlined later on; it is with this in mind, however, that the following table has been made. Many of the correlations are only provisional, and will probably require adjustment and rearrangement as the result of future investigation; but it is believed that the general deductions are correct.

By this correlation we see that the succession of lavas seems to have been roughly uniform over the whole region, although minor variations have been numerous at many points. In general, it appears possible to divide the lavas into five groups, in the order of their eruption, as follows:

1. Acid (type, biotite rhyolite).
2. Siliceous intermediate (medium andesites).

[1] W. H. STORMS: Eleventh Rept. State Mineralogist California, p. 347. Sacramento, 1893.

3. Acid (rhyolites with composition like 1) with occasional connected basalts.
4. Basic intermediate (more basic andesites and aleutites).
5. Basic (basic basalts), frequently with closely connected rhyolites.

CORRELATION OF LAVA GROUPS IN POINT OF AGE

The absolute age of the different Tertiary lavas is not easy to find out, although in many special cases it may be done with a fair degree of accuracy. The most recent eruptions are naturally the most easy of determination, while those more remote are more obscure.

1. *Acid.*—In the Pine Nut and Sweetwater ranges the definite age of the older rhyolites is uncertain, but they are separated from the great bodies of massive hornblende-pyroxene-biotite andesite, which itself antedates the Pliocene Shoshone Lake, by a long period of erosion. These rhyolites are also affected by a sheeting which is not found in the andesites, and which indicates crustal disturbance between the eruption of the two lavas.

The observations concerning the Pine Nut and Sweetwater ranges are in general true, also, for the Reveille, Quinn Canyon, and Grant ranges.

In Meadow Valley Canyon the basal rhyolite, with its overlying tuffs, is folded and separated by a marked unconformity from the andesitic lavas and tuffs which succeed. The rhyolite tuffs are roughly estimated at 4000 feet thick, and mark a long period of Tertiary sedimentation, which intervened between the rhyolites and the andesites.

In the Silver Peak region rhyolites are interbedded in portions of the Tertiary lake sediments, which are probably late Eocene or early Miocene.[1]

In the Panamint Range, in the Randsburg district, and near Daggett in the Mojave Desert, lake beds which are probably in part at least Upper Eocene overlie the basal rhyolite.

In general, therefore, it may be said that the age of the rhyolite, which is the first member of the general succession,

[1] H. W. TURNER: The Esmeralda Formation. Am. Geol., Vol. XXX, March 1900, p. 168.

varies in different portions of the petrographic province from early to late Eocene. Strict contemporaneity is not to be expected, but only broad correspondence.

2. *Siliceous intermediate*.—In the region of the 40th Parallel Survey, Mr. King[1] considered that the beginning of Miocene time came between the main period of the hornblende andesites (No. 2 of the succession here outlined) and that of the augite andesites (No. 4 of this succession). Mr. King found his Miocene beds (sediments of the Pah-Ute Lake) largely made up of tuffs derived from what was at that time regarded as trachyte, and he therefore considered the trachytic period as Miocene. The trachytes of the 40th Parallel Survey have been shown to be mainly andesites, in part hornblende-mica andesites and in part pyroxene andesites.[2]

In the Virginia, Pine Nut and Sweetwater ranges, the hornblende-pyroxene-biotite andesites were erupted and eroded previous to the formation of the Shoshone Lake, to which they formed the shores. The Shoshone Lake probably existed in late Pliocene and earliest Pleistocene time; this puts back the age of these andesites to at least early Pliocene.

In the Silver Peak region andesites occur, together with abundant andesitic tuffs, in portions of the Esmeralda formation, which is probably late Eocene or early Miocene.

In the El Paso Range, according to Fairbanks, andesite occurs as interstratified sheets in the late sediments of the Upper Eocene.

Taken altogether, it may be said that the period of eruption of the medium-siliceous andesitic lavas was chiefly in the Miocene, although it probably ran back to the Upper Eocene. The periods of eruption No. 1 and No. 2 therefore overlap, and they are actually found close together in certain of the Upper Eocene lake sediments.

Acid.—Concerning the age of the third member of the succession there are somewhat better data. In the 40th Parallel

[1] Explorations of the 40th Parallel, Vol. I, p. 692.

[2] HAGUE and IDDINGS: Volcanic Rocks of the Great Basin. Am. Jour. Sci., 3d series, Vol. XXVII, January 1884, p. 456.

region Mr. King[1] notes that the rhyolites and rhyolite tuffs seem to be Pliocene. In the Eureka district Mr. Hague[2] came to the same conclusion as regards the rhyolite there.

In western Nevada rhyolities are found interbedded and therefore contemporaneous with the sediments of the late Pliocene Shoshone Lake in a number of localities, as, for example, on the borders of the Pine Nut Range. The same relation to the Shoshone Lake beds was noted on the western edge of the Ralston Desert.

In the mountains near Candelaria glassy rhyolite overlies the folded Upper Eocene or Lower Miocene of the Esmeralda formation. The folding which has affected these beds is the same as that which has upturned the Miocene further north, called by King the Truckee Miocene; so the disturbance must have been late Miocene or post-Miocene. The rhyolite in this case, therefore, is probably as young as the Pliocene.

In the Sierra Nevada Mr. Turner[3] referred the rhyolites to the Upper Miocene. According to Mr. Lindgren[4] the rhyolitic flows of the Sierra in the Truckee region began "toward the close of the Miocene."[5]

In general, therefore, the age of the second chief rhyolite eruption ranges from late Miocene well into the Pliocene.

Basic intermediate. — In the Sierra Nevada, according to Turner,[6] the pyroxene andesite is Pliocene.

[1] Explorations of the 40th Parallel, Vol. I, p. 694.

[2] Mon. U. S. Geol. Surv., Vol. XX, p. 232.

[3] Igneous Rocks of the Sierra Nevada, JOUR. GEOL., Vol. III, No. 4, May-June 1895, p. 406; Auriferous Gravels of the Sierra Nevada, Am. Geol., June 1895, p. 372.

[4] Truckee folio, U. S. Geol. Surv., p. 3.

[5] The writer was at first inclined to correlate the rhyolite of the Sierra Nevada with the earliest rhyolite shown in the general correlation table (No. 1 of the general succession); but a number of considerations, among others that of the comparatively slight age of the Sierra Nevada rocks, as given above, induced him to class them with later rhyolites (No. 3 of the general succession). In agreement with this conclusion are Hague's views (Mon. XX, U. S. Geol. Surv., pp. 261, 281.

[6] Age and succession of the Igneous Rocks of the Sierra Nevada, JOUR. GEOL. Vol. III, June 1895, p. 408.

In the Sweetwater Range, near Wellington, pyroxene andesite flows are found intercalated with the sediments of the great Pliocene Shoshone Lake.

In the Schell Creek, Antelope, and Snake ranges the pyroxene aleutite, which overlies glassy biotite rhyolite, has filled up valleys which are probably early Pliocene, and has suffered only slight erosion, resulting in the development of a narrow Pleistocene valley, since that time. It can hardly, therefore, be older than late Pliocene.

On the whole the main period of eruption of the basic intermediate lavas appears to have been during the Pliocene, and chiefly the late Pliocene. Most of the great andesitic breccias, indicating widely distributed explosive eruptions, seem to belong to this period.

5. *Basic*.—In the Eureka district it is suggested that the latest outbursts, which were of olivine-basalt, occurred in the Pleistocene.[1]

Near Steamboat Springs, which is just west of the southern end of the Virginia Range and in the immediate district of the Comstock lode, the writer observed that the olivine-basalt is probably early Pleistocene, since it has filled the valleys and covered the scarps eroded by the late Pliocene and early Pleistocene Shoshone Lake.

On the borders of the Pine Nut Range the basalt appeared after the Shoshone Lake had shrunk to the later Pleistocene Lake, and after the country exposed by this recession had been partly dissected into canyons. It is therefore plainly of Pleistocene age.

In the Ralston Desert and in the Reveille and Pancake ranges the basalt overlies the Pliocene sediments, supposed to belong to the Shoshone Lake period. In the Quinn Canyon and Grant ranges the basalt has been poured out into valleys which were probably formed in the late Pliocene period.

In most of the other localities where this lava has been found there is little doubt that the age is Pleistocene, although some of the eruptions may date back to the late Pliocene.

[1] Mon. U. S. Geol. Surv., Vol. XX, p. 232.

TABULATION

The relative age of the different members of the volcanic section, therefore, may be roughly outlined in the following table. It must be remembered that this is only approximate.

The age of the members of volcanic succession being determined, we can sometimes apply this determination in cases where the age of the lavas cannot be independently ascertained, and use them roughly as time markers.

Epochs of sedimentation	Standard time divisions	Epochs of vulcanism
	End of Cretaceous	
	Eocene	No. 1. Acid (type, biotite rhyolite)
Eocene-Miocene Lakes	Miocene	No. 2. Medium intermediate (type, hornblende-mica-pyroxene andesite)
		No. 3. Acid (type, biotite rhyolite)
Shooshne Lake	Pliocene	No. 4. Basic intermediate (types, pyroxene, andesite, etc.)
Lake Lahontan Walker Lake, etc.	Pleistocene	No. 5. Basic and acid (basalts and occasional rhyolites)

LAW OF SUCCESSION OF LAVAS

The most natural deduction from all these harmonious observations is that the Great Basin, southward into the Mojave Desert, together with a portion at least of the Sierra Nevada, constitutes a petrographic province; that is to say, it is underlain by a single body of molten magma, which has supplied, at different periods, lavas of similar composition to all the different parts of the overlying surface. The limits of this subcrustal basin, however, are not yet defined in any direction.

In studying the eruption of different lavas from this magma basin at different periods, it is instructive to inquire whether or not the succession follows any definite laws. Mr. Iddings[1] interpreted the usual law of succession in volcanic rocks as this: that a series begins with a rock of average composition, and passes through less siliceous and more siliceous ones to rocks extremely high in silica and others extremely low in silica—that is, the series commences with a mean and ends with extremes. This interpretation of Iddings was based on his work in the Yellowstone Park and vicinity, at Eureka, Washoe, and elsewhere. From studies of the eruptive rocks in the vicinity of Christiania Professor Brögger also thought to have determined a definite law of succession, by which the lavas progress from the most basic to the most acid varieties. Sir Archibald Geikie,[2] from a study of igneous rocks in Great Britain, has come to the same general conclusion as to the succession.

The section of Tertiary volcanics exposed at Eureka and Washoe, as given by Mr. Hague, begins with what is designated by the present writer No. 2 in the succession, and does not reach back to the basal biotite rhyolite. The general succession for the Great Basin, leaving out this basal rhyolite, appears, then, to be as follows:

2. Siliceous intermediate.
3. Acid (and basic).
4. Basic intermediate.
5. Basic (and acid).

[1] The origin of igneous rocks, Bull. Phil. Soc. Washington, Vol. XII, p. 145.

[2] Quar. Jour. Geol. Soc. Lond., 1892, Vol. XLVIII, p. 177.

Under No. 5 we find the very basic olivine-basalts and very siliceous rhyolites or tordrillites, erupted at the same period and evidently connected by the closest ties. This, for example, was observed to be the case in the Pleistocene volcanics of the Meadow Valley Canyon, and the same is true in the basin of Lake Mono, according to Russell.[1]

These closely allied ultra-basic and ultra-acid lavas are plainly complementary forms, and are proofs of differentiation as convincing as are the complementary segregations so familiar in single masses of intrusive or plutonic rocks.

Going a little further, if we write Nos. 3 and 4 of this last succession together and precede it by No. 2 (which we may divide into two members) we have the following grouping:

2. { Medium andesite.
   Acid andesite and dacite.

3. { Acid rhyolite (with basalt).
4. Medium basic andesite.

5. { Basalt.
   Acid rhyolite.

We have here, therefore, a series (apparently conformable to Iddings' law) which begins with a rock of intermediate composition and progresses to extremes, as a result, probably, of differentiation.

But the first member in the order of succession as interpreted by the writer, viz., the basal rhyolite, is apparently out of place in this scheme. This rock has a composition essentially like the later rhyolite, but appears to have no immediate connection, mineralogically or chemically, with the andesites which form the base of the Eureka lavas. The andesites can hardly be derived from the rhyolites by any hypothetical differentiation, and even in that case the order seems in direct opposition to all of the hitherto propounded laws of succession.

It was first, therefore, the conclusion of the writer that the law deduced by Iddings would not hold good in the Great Basin, on

[1] Quaternary history of Mono Valley, California: Eighth Ann. Rept. U. S. Geol. Surv., Part I.

account of the basal rhyolite. From further study, however, the evidence of differentiation up to this point appears to be so good that he is inclined to accept it, and to consider the basal rhyolite as belonging to a different order of events.

This basal rhyolite is, in chemical and mineralogical composition, much like the latest rhyolite, No. 5, in the writer's order of succession. Like it, it often becomes extremely siliceous. From this circumstance, and from the apparent break in composition between the rhyolite No. 1 and the andesite No. 2, the writer conceived the idea that the two rhyolites are *recurrent* lavas—that is, that they represent a similar development in distinct but similar processes of differentiation. The development of lavas might then be interpreted as follows:

1. Acid rhyolite.
   Revolution and beginning of new epoch.
2. Medium to acid andesite and dacite.
3. Acid rhyolite (with basalt).
4. Medium basic andesite.
5. { Basic basalt.
   { Acid rhyolite.

In case this is the current grouping, it is probable that No. 1 represents the end product of a differentiation, and is similar to the rhyolite under No. 5; and that 2 to 5 inclusive represent an independent differentiation process.

The difficulty with the above arrangement is, first, the olivine-basalt, which we are obliged to couple with the rhyolite under No. 3. The existence and relations of this basalt in the Sierra Nevada seems to be well established. The second difficulty arises from the fact that the rhyolite No. 3 is of exactly the same acid type as the rhyolites under 1 and 5. From this fact the idea originates that rhyolite No. 3 may be also a recurrent lava, and that we have in the whole volcanic succession portions of three instead of two cycles of differentiation.

On testing this hypothesis we are struck with the fact that andesites 2 and 4 have identical phases, although the groups as a whole differ as stated in the above list. At Eureka the earlier and later andesites were held to be separate, the earlier ones

being more siliceous and not approaching the later ones more nearly than by 2.25 per cent. of silica.[1] At Washoe, however, the pyroxenic andesites, which precede the more siliceous andesites representing at Eureka the earlier group, become equally basic with the andesites of the second period. In other portions of the Great Basin also the andesites belonging to the first and second periods are often indistinguishable.

On studying the general succession, as partially set forth in the table of correlations, we find that the break between Nos. 3 and 4 in the succession is as abrupt as that between Nos. 1 and 2. On the other hand, between 2 and 3 there are many transitional phases, and also between 4 and 5.

We may represent the facts above noted, graphically, as follows:

1. Rhyolite.
2. Andesite.
3. Rhyolite (and basalt).
4. Andesite.
5. Basalt (and rhyolite).

The break between 3 and 4 was noted by Mr. Hague at Eureka.[2] He ascribed it to a change of magmas and argued that the first members of the succession at Eureka, beginning with hornblende andesite and ending with acid rhyolite, were derived from a magma distinct from that which produced the later members of the succession, beginning with pyroxene andesite and ending with basalt. In the first group Mr. Hague found, between the andesite and the rhyolite, gradual transitions which grew continually more siliceous; likewise in the second group he found gradual transitions between the pyroxene andesite and the basalt. This implies two distinct processes of differentiation, the first of which proceeded from intermediate to acid, while the second followed the opposite order, from intermediate to basic. Mr. Hague's interpretation of the development of lavas at Eureka may be graphically represented as follows:

[1] Monograph XX, U. S. Geol. Surv., p. 269.

[2] Monograph XX, U. S. Geol. Surv., pp. 254, 269, 270, 271.

$$\text{Feldspathic Magma}\begin{cases}\text{Hornblende Andesite.}\\ \downarrow \quad \text{Series growing gradually more siliceous.}\\ \text{Acid Rhyolite.}\end{cases}$$

$$\text{Pryoxenic Magma}\begin{cases}\text{Pyroxene Andesite.}\\ \downarrow \quad \text{Series growing gradually more basic.}\\ \text{Basalt.}\end{cases}$$

The *general* succession in the Great Basin region, as set forth in the table which we have made opposite this page, corresponds to Mr. Hague's conception (leaving out of the question the rhyolite No. 1, which is not exposed in the Eureka district). The relations of the lavas of the whole region, therefore, omitting the minor exceptions, might be represented as follows:

1. Rhyolite.

 Break.

2. Andesite.

 $\downarrow$ Gradual transitions.

3. Rhyolite.

 Break.

4. Andesite.

 $\downarrow$ Gradual transitions.

5. Basalt.

Nevertheless, the exceptions are frequent enough to demand recognition. Observations at several points outside of the Eureka district prove that basalt No. 5 has a closely associated rhyolite which is plainly complementary. Similarly, rhyolite No. 3 has in the Sierras an associated olivine-basalt, which is also probably complementary. Upon looking carefully, we find that there are complementary phases for the stages intermediate between the andesite No. 4 and the basalt No 5; and we become

	Eureka (Hague)	Washoe (Hague)	Sierra Nevada (Turner)	Sierra Nevada (Ransome)	Tintic Range, Utah (Tower and Smith)	Lake Mono (Russell)
I						
2	Hornblende andesite Hornblende mica andesite Dacite	Pyroxene-hornblende andesite (diorite and diabase) Hornblende-mica andesite (mica diorite, diorite porphyry) Dacite				Hornblende and site
3	Rhyolite	Rhyolite	Rhyolite Basalt	Biotite rhyolite Olivine-basalt	Biotite rhyolite	
4	Pyroxene andesite	Pyroxene andesite	Hornblende-pyroxene andesite, tuffs, and breccias Pyroxene andesite	Hornblende-pyroxene andesite breccia Latites { Augite-biotite-hornblende latite; Biotite-augite latite } Hornblende-pyroxene andesite breccia	Pyroxene-hornblende-biotite andesite, tuffs, and breccias Pyroxene-hornblende andesite (latite and monzonite)	
5	Basalt	Basalt (diabase)	Basalt	Olivine-basalt	Olivine-basalt	Basalt Hypersthene and site, verging o basalt Rhyolite

CORRELATION OF TERTIARY LAVAS IN ~~GREAT BRITAIN~~ the Great Basin.

ke Mono Russell)	Pine Nut Range	Sweetwater Range	Gabb's Valley	Ralston Desert	Schell Creek Range	Egan Range	Meadow Valley Canyon
	Biotite rhyolite (granite and alaskite)	Rhyolite (granite)		Rhyolite Tordrillite			Biotite rhyolite
lende ande-	Hornblende-pyroxene-biotite andesite Hornblende-biotite andesite	Hornblende-pyroxene andesite	Biotite andesite			Dacite-andesite	
	Rhyolite		Biotite rhyolite	Rhyolite	Biotite rhyolite		
	Hornblende-pyroxene andesite, tuffs, and breccias	Hornblende-pyroxene andesite, tuffs, and breccias Hornblende biotite latite (breccia)	Hypersthene-hornblende aleutite		Pyroxene aleutite		Pyroxene andesite breccia and tuff, Biotite-hornblende quartz-latite Biotite-hornblende dacite Biotite-hornblende rhyolite
sthene ande- verging on lt te	Rhyolite Basalt (hornblende basalt)	Basalt	Augite basalt	Olivine-basalt		Basalt	Rhyolite Pyroxene olivine-basalt Rhyolite-tordrillite

N ~~GREAT BRITAIN~~ the Great Basin.

Range	Gabb's Valley	Ralston Desert	Schell Creek Range	Egan Range	Meadow Valley Canyon	Panamint Range	Randsburg Region
ranite)		Rhyolite Tordrillite			Biotite rhyolite	Rhyolite	Biotite rhyolite
e-pyrox- esite	Biotite andesite			Dacite-andesite		Andesite	
	Biotite rhyolite	Rhyolite	Biotite rhyolite				
-pyrox- te, tuffs, as biotite ccia)	Hypersthene- hornblende aleutite		Pyroxene aleutite		Pyroxene andesite breccia and tuff, Biotite-hornblende quartz-latite Biotite-hornblende dacite Biotite-hornblende rhyolite		Hornblende- pyroxene- biotite aleutite
	Augite basalt	Olivine-basalt		Basalt	Rhyolite Pyroxene olivine- basalt Rhyolite-tordrillite	Pyroxene aleutite and basalt (often olivine- bearing)	Pyroxene basalt Pyroxene olivine- diabase por- phyry (dike)

aware that these complementary forms constitute an acid-growing series, transitional between the andesite No. 4 and the rhyolite which is complementary with No. 5, and that this series appears to be in general contemporaneous with the basic-growing series between the andesite and the basalt. As an example of this acid-growing series consecutively observed, the section described in Meadow Valley Canyon is highly interesting; here we have a transition from pyroxene andesite through intermediate phases to Pleistocene rhyolite, which is complementary with Pleistocene basalt.

Between the andesite No. 2 and the olivine-basalt which is coupled with the rhyolite No. 3, we have not found such satisfactory transition phases, but this is perhaps due to the remoter age of this group of lavas.

We may, therefore, write the general succession and relation of the lavas of the Great Basin, as follows:

1. BIOTITE RHYOLITE AND TORDRILLITE.

2. PYROXENE-HORNBLENDE ANDESITE.
   - Hornblende-pyroxene andesite.
   - Hornblende andesite.
   - Biotite andesite.
   - Hornblende quartz-andesite.
   - Dacite.
   - Latite (?)[1]
   - Pyroxene andesite (?)

3. BIOTITE RHYOLITE. OLIVINE-BASALT.

[1] Compare some of the analyses of the earlier andesites and dacites at Eureka (e. g., Mon. XX, U. S. Geol. Surv., p. 264, Nos. 4, 5, and 6), with those of latites given by DR. RANSOME (Bull. 89, U. S. Geol. Surv., p. 66).

PYROXENE-HORNBLENDE ANDESITE.

	Pyroxene andesite.	Hornblende-pyroxene andesite.
4.	Hornblende-pyroxene-biotite aleutite.	Augite-biotite-hornblende latite.
	Hypersthene-hornblende aleutite.	Biotite-augite-hornblende quartz-latite.
	Pyroxene aleutite.	Biotite-hornblende dacite.
	Pyroxene olivine-aleutite.	Hornblende-biotite latite.
5.	Hornblende basalt.	Biotite-hornblende rhyolite.
	Augite basalt.	Biotite rhyolite.
	OLIVINE-BASALT.	ULTRA ACID RHYOLITE OR TORDRILLITE

It therefore appears that we have the representatives of two complete cycles of differentiation, and probably the end of a still earlier cycle. During the first completely recorded cycle (beginning with the earlier andesites) the more siliceous rocks were continually extravasated in preference to the more basic complements, so that the acid-growing series is far more prominent in the record than the basic-growing one. On the contrary, during the second or last complete cycle the more basic rocks were continually thrown out in preference to the more siliceous ones, making the basic-growing series more prominent. The laws which govern these apparently eccentric preferences of eruption are yet unknown.

I have looked in vain in the field for the earlier representatives of the first cycle of differentiation, to which No. 1 belongs. If they were erupted previous to the appearance of the rhyolite (No. 1) they have not yet been determined.[1]

[1] What may possibly be one of the members of the earlier differentiation cycle, older than the rhyolite, occurs in the Walker River Range. Here the granite and alaskite, which are considered by the writer as probably the deeper-seated equivalents of the basal rhyolite of the Great Basin section, are evidently younger than and at times intrusive into a great body of biotite-hornblende quartz-monzonite. A similar hornblende-biotite quartz-monzonite was found east of the Walker River Range, in Gabb's.

Reasoning on the basis of the deductions specified, we may speculate briefly concerning the cause of the two revolutions, the reappearance of the intermediate magma, and the exhaustion of the old, highly differentiated magmas. In explanation of this, the hypothesis may be advanced that magma basins or lava reservoirs may be almost entirely exhausted by the expulsion of lavas to the surface, and that this emptying may permit refilling by new material from lower regions.[1] It is very possible that the processes of differentiation can only go on under certain circumstances, such as are probably afforded by the comparatively quiet magma basins, and that in the lower regions there may be so much mixing that segregation is impossible.[2] Therefore, when the magma basin is exhausted and receives a new supply from below, it is of material similar to that which filled the basin before differentiation altered it. It is probable that in this way the history of many petrographic provinces, when closely studied far back into geologic time, will be found to be not a simple, single process, but a succession of several or many differentiation cycles, some of which will probably be found to be complete, and some interrupted by this or that accident. It is probable that the existence of recurrent lavas will be found true at many points.[3] In Alaska the writer has found that the

Valley, and here was considered to be extrusive. The writer's grounds for considering that the Walker River Range granite is equivalent to the basal rhyolite cannot be given in this paper, but will appear subsequently. If they prove sound, then the older monzonite very likely represents a pre-rhyolitic monzonitic effusive rock, or at least a less siliceous pre-rhyolite magma.

[1] Since writing the above the writer has chanced upon the following sentence of IDDINGS ("Origin of Igneous Rocks:" Bull. Phil. Soc., Washington, Vol. XII, 1892–4, p. 179): "It is also possible to find a recurrence of different varieties at one center of eruption, which may be accounted for by supposing successive supplies of magma from some depth, which differentiate into similar varieties before their final eruption," He also finds that the same idea had been previously expressed by Sir Archibald Geikie (Quar. Jour. Geol. Soc., London, Vol. XLVIII, 1892, p. 178), as follows: "And as the successive protrusions took place within the same circumscribed region, it is evident that in some way or other, during the long interval between the two periods, the internal magma was renewed as regards its constitution, so that when eruptions again occurred they once more began with basic and ended with acid materials."

[2] IDDINGS (op. cit., p. 196) considers that the general or undifferentiated magma remains undifferentiated on account of being solid, that is, being in a state of potential liquidity.

[3] GEIKIE (op. cit.) in his study of the history of volcanic activity in Great Britain

probably Silurian basalt or basaltic diabase of the Rampart series is identical in composition with the olivine-basalts of the Pliocene.[1] Yet between these two periods a great variety of volcanic rocks, including other basalts, appeared in Alaska.

In studying the succession of lavas it must be borne in mind that the processes of differentiation are quite independent of the causes which produce the expulsion of lavas. Therefore, while the differentiation in a magma basin may go on so that all intermediate types between the initial intermediate one and the final extremes are represented, yet the causes producing eruption will probably occur only at different points in this process, so that the record will be only partial and perhaps not to be interpreted except by comparison with other localities. For this reason, the observed succession must be studied with regard to its general aspects rather than to its details. In interpreting the succession, also, the possibility, or even probability, of many intermediate forms being brought about by accidental mixing during the general processes of differentiation, must be borne in mind. This error may be eliminated if at each period of vulcanism we select the extreme important types, omitting the associated intermediate ones as possibly formed by mingling. The variations introduced by mingling and those brought about by irregular volcanic eruptions are such that it is difficult to apply to them any law. It has been assumed, for example, that in general basalts overlie rhyolites where these occur close together. This is held by Messrs. Hague and Iddings[2] as well as by previous observers. But Marvine[3] observed, in the Colorado River region, basalt lying upon rhyolite, and the present writer observed the same relation in the Pleistocene lavas of Meadow Valley canyon, which is a part of the drainage of the Colorado.

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from the earliest pre-Cambrian times to the Tertiary, has found that similar rocks recur at many different points in the succession. He finds also similar series, so that he is led to divide the whole succession into natural groups or periods of volcanic activity. See also IDDINGS, op. cit., pp. 145, 179, 196.

[1] Geology of the Yukon Gold District. Eighteenth Ann. Rept., U. S. Geol. Surv., Part III, Economic Geology, p. 241.

[2] Mon. U. S. Geol. Surv., Vol. XX, p. 86.

[3] U. S. Geol. Surv., W. 100th Mer., Part III, p. 205.